Simulation of storm surge and overland flows using geographical information system applications

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Abstract

This study focuses on a few aspects of an on-going project at Jackson State University regarding homeland security in the state of Mississippi. The project proposes an integrated tool for multi-scale storm surge and overland flow (flood) forecast due to hurricane, as well as evaluation of the flood damage on coastal infrastructure including transportation systems in the Mississippi coast. Three models are executed in sequence to get all the necessary results. Two out of these three codes are extensively parallel to ensure real time forecast to deal with the emergency evacuation days before the hurricane strikes the coast. The results from the models are fed into Geographical Information Systems (GIS) for visualization, analysis and decision-making.
Keywords: multi-scale hurricane simulation, meteorological data, overland flow, parallel computation.

1 Introduction

In this study, we present an integrated modelling scheme of a hurricane from its approach to landfall and associated water surge and flooding in the coastal regions. Using the most updated meteorological data days before a hurricane strikes, the ground wind speed, pressure, rain, etc can be predicted using the open source parallel code Weather Research and Forecasting (WRF) [1]. We obtain wind speed and pressure data from WRF, which are used as input to another open source parallel code ADvanced CIRCulation (ADCIRC). ADCIRC is a model for oceanic, coastal and estuarine waters [2]. We use ADCIRC results

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to model the coastal area flooding phenomena using our finite element method based CaMEL Overland flow solver [3]. The water surge values simulated from ADCIRC along the shoreline is used as the Dirichlet boundary condition input to CaMEL Overland. The rain data predicted from WRF is used as the source term in this solver. The graphical presentation in fig. 1 shows the integration of the whole simulation process.

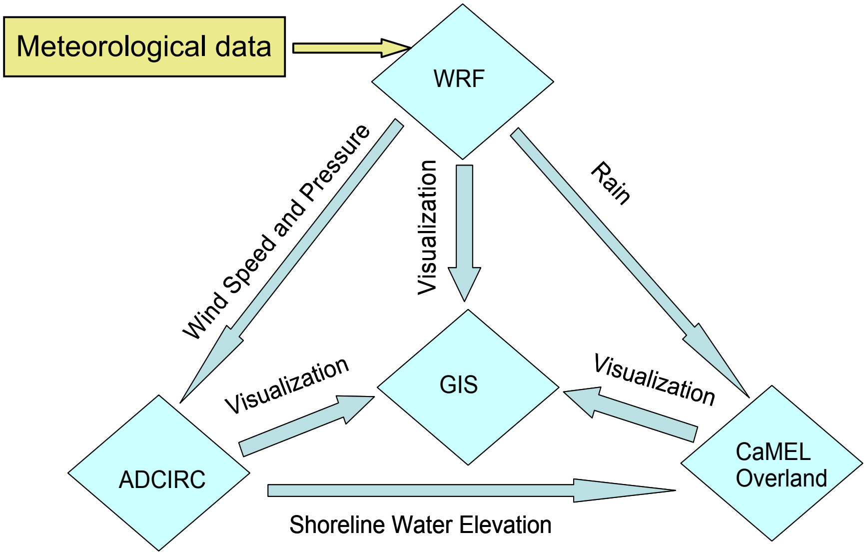


Figure 1: Graphical representation of our integrated modelling scheme.

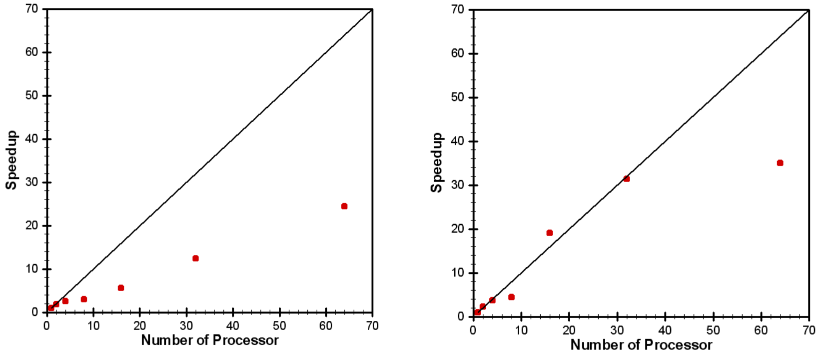
In an actual hurricane case WRF, ADCIRC, and CaMEL Overland codes must be executed in sequence two to three days before its landfall, most likely every 6 to 12 hrs. Repeated simulations of the codes are needed because the more recent meteorological data we use the better accuracy we obtain from WRF. The accuracy of WRF results propagate into ADCIRC and CaMEL Overland simulations through the wind and rain input. Therefore, parallel implementation of the codes is absolutely necessary to ensure real time hurricane and flood forecast.

As a case study in the present research, we have chosen hurricane Katrina (2005) and its flooding impact on the Mississippi coastal region.

2 Model implementation

WRF is a parallel model, which is designed to serve both operational forecasting and atmospheric research needs. It is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers. It allows researchers the ability to conduct simulations reflecting either real data or idealized configurations. We have studied the parallel implementation of WRF extensively in our parallel cluster, which has Intel Xeon processors and total of 80 cores. The speed up of WRF in our cluster is displayed in fig. 2 (a). WRF uses structured mesh with the option of multiple nested domains. We used a single domain with 300 grid points in east-west, and 220 grid points in south-north. Each segment was 8 km.

Using the WRF wind speed and pressure data as input, ocean water surge is simulated using two-dimensional depth integrated (2DDI) model of ADCIRC. ADCIRC is a highly developed computer program for solving the equations of motion for a moving fluid on a rotating earth. These equations have been formulated using the traditional hydrostatic pressure and Boussinesq approximations and have been discretized in space using the finite element method and in time using the finite difference method. The water elevation is obtained from the solution of the depth-integrated continuity equation in Generalized Wave-Continuity Equation (GWCE) form. The speed up of ADCIRC in our parallel cluster is displayed in fig. 2 (b). The ADCIRC grid used in our simulation is the same as Mukai et al. [4], which consists of 254,565 nodes and 492,179 elements. ADCIRC Tidal Database [3], Version ec2001_v2d, is used to extract tide data during the Katrina period. Zero-flux boundary conditions are used on the land boundary, and tidal conditions are used in the ocean boundary.



(a) (b)

Figure 2: Code speedup with respect to the number of processors in our cluster. (a) WRF, (b) ADCIRC.

After the ADCIRC simulation, we model the coastal area water surge phenomena using our CaMEL Overland flow code. We have solved diffusive wave or Richard's equation, as shown in (1), by the Galerkin finite element method [3]. The time dependent water surge values simulated from ADCIRC along the shoreline is used as the Dirichlet boundary input in the model. The rain data predicted from WRF is used as the source term in the model. Since the execution of CaMEL Overland code is very fast, we have not made any attempt to make it parallel yet. We, however, will make it parallel soon.

$$\frac{\partial h}{\partial t} - \nabla \cdot \left(K \nabla h \right) = \dot{q} \tag{1}$$

where, h, K, $\dot{q}$ are water elevation, diffusion coefficient, and source terms, respectively.

3 Results and discussion

WRF simulation results heavily depend on the meteorological data. Hurricane may take unexpected turns, which only the latest meteorological data may reflect. Hurricane landfall location has a huge impact on ocean water surge. Experience suggests that water rises rapidly if the hurricane hits Louisiana coast, most likely due to the converging funnel effect of complicated land structure. On the contrary, hurricane hitting the Alabama coast is most likely to cause much lesser water surge. The computer modelling done by other researchers suggests that the funnel effect in Louisiana area may increase the surge by 20 to 40 percent [5]. This funnel-effect fact is particularly very much applicable for Katrina (Aug 23-31, 2005) type hurricanes with twisted track paths.

Figure 3 shows the comparison of Katrina simulation and actual track path. Figure 3(a), (b), (c), and (d) show the WRF simulated track paths starting from Aug 26 - 00 A.M., Aug 27 - 00 A.M., Aug 27 – 12 P.M., and Aug 29 - 00 A.M., respectively. Figure 3 (e) shows the actual track path obtained by using the Planetary Boundary Layer (PBL). Note that the PBL method interpolates the wind information from the published meteorological data for already past events. The published track path of Katrina is shown in fig. 3 (f). From the comparison with fig. 3 (e) and (f), fig. 3(a) and (b) show that these WRF simulation were started too early. These landfall locations are somewhat east of the actual one. Figure 3(c) appears to have the best result. Although fig. 3(d) had the latest meteorological data, the hurricane was already too close to the land and it appears to subside. WRF seems to work best with latest meteorological data, while the hurricane is still at least 24 hr far away from the land. This fact underlines the importance of parallel simulation of WRF for quick delivery to facilitate r safe and quick evacuation during an actual hurricane.

Katrina ocean water elevation plots from ADCIRC with different wind speed and pressure input from WRF or Planetary Boundary Layer (PBL) are displayed in fig. 4. Figure 4 (a)-(c) use WRF wind input with different starting date and time, while fig. 4(d) uses actual Katrina wind data provided by PBL. From the comparison of fig. 4(a) – (c) with fig. 4(d), it is evident that the starting date of WRF simulation has huge impact on the results. It is because of the fact that the latest meteorological data in WRF generates more accurate wind speed, pressure, and landfall location of hurricane. The impact subsequently is carried to ADCIRC and CaMEL Overland codes. In addition to that, ADCIRC simulation has to be done for several days around the hurricane period, typically for 5-7 days, to get reasonably good results. Longer simulation period captures both short and long ocean waves. All the facts mentioned above emphasize the

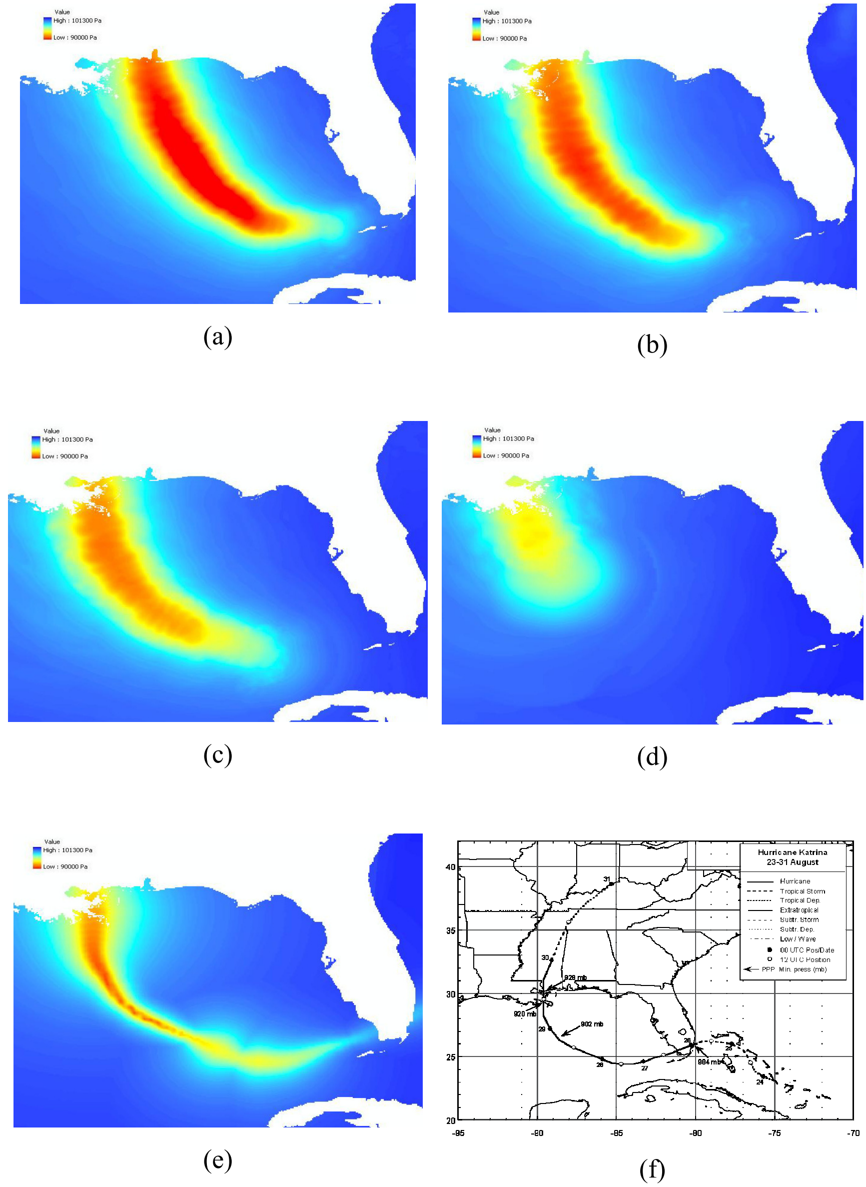


Figure 3: Katrina wind pressure plots (a) WRF simulation starting from Aug 26, 00 A.M., (b) WRF simulation starting from Aug 27, 00 A.M., (c) WRF simulation starting from Aug 27, 12 P.M., (d) WRF simulation starting from Aug 29, 00 A.M., (e) Actual, using Planetary Boundary Layer (PBL) (Aug 23 to Aug 31), (f) Published track path.

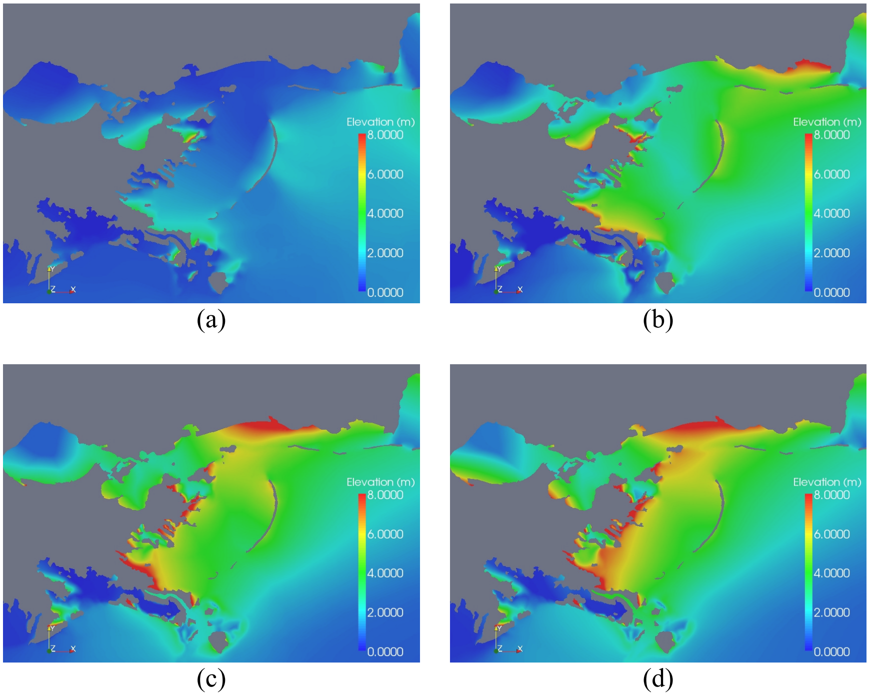
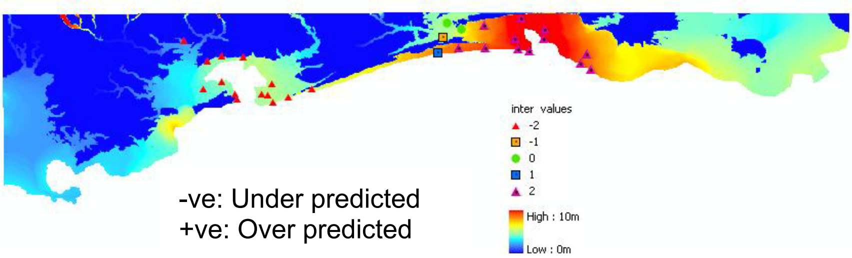


Figure 4: Comparison of ADCIRC simulation for different (WRF vs. PBL) wind speed and pressure data as input. (a) WRF - starting date Aug 26, 2005, 00 hr, (b) WRF - starting date Aug 27, 2005, 00 hr, (c) WRF - starting date Aug 27, 2005, 12 hr (d) Actual wind data from PBL (Aug 24 to Aug 31).

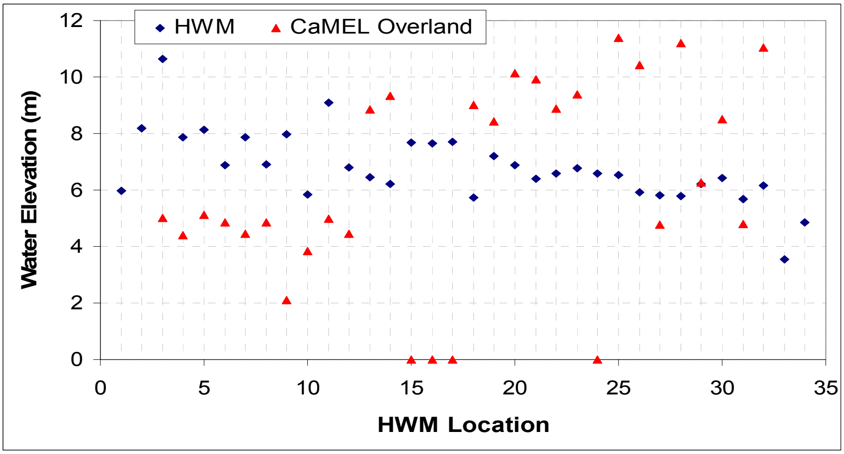
importance of parallel implementation of the codes for real time hurricane forecast to help effective evacuation.

Katrina High Water Mark (HWM) simulated from CaMEL Overland code is displayed in fig. 5(a). This plot is generated using WRF wind speed and pressure data without rain source terms. HWM values were recorded at many observation locations after the Katrina. The simulated HWM values are interpolated at the 32 observation locations and compared with the observed data. The numbers in the legend ‘inter values’ mean the difference range between the observed and simulated HWM in meters. For example, if the ‘inter values’ reads -2 in an observation location, it means the simulation under-predicts the HWM and the difference is within 2 meters. This result can be used to predict whether any structure in the domain will be flooded, damaged, or unaffected because of the water surge. This is one of the most important information that will help setting up the evacuation plan.

Figure 5(b) shows the comparison of simulated Katrina HWM with the observed ones for all 32 observation stations. The discrepancies in the



(a)



(b)

Figure 5: CaMEL Overland model Katrina results. (a) HWM in the coastal region, (b) Comparison of observed and simulated HWM.

comparison arise primarily because the simulation scheme is integrated. That means, error in WRF propagates to ADCIRC and overland models; and error in ADCIRC propagates to overland model. From our experience, getting an exact prediction is hard to achieve with the current technology available. However, we may be able to provide with the possible worst and best case scenarios during an actual hurricane event.

4 Conclusions

We have presented an integrated modelling scheme of a hurricane from its approach to landfall and associated water surge and flooding in the coastal regions using WRF, ADCIRC, and CaMEL Overland codes. We have demonstrated that repeated simulations of the codes are needed because the more recent meteorological data we use, in general, the better accuracy we obtain from WRF. The accuracy of WRF results propagate into ADCIRC and CaMEL

Overland simulations through the wind and rain input. We have emphasized the importance of parallel implementation of the codes to ensure real time hurricane and flood forecast for safe evacuation.

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